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CHARACTERISTICS OF MAGNETOSHEATH PLASMA OBSERVED AT LOW ALTITUDES IN THE DAYSIDE MAGNETOSPHERIC CUSPS

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ABSTRACT

Magnetosheath plasma penetrating to low altitudes in the dayside cusp region of the magnetosphere has been observed by the ISIS 1 soft particle spectrometer (SPS). The extent of these particle fluxes in local magnetic time and invariant latitude, their variation with magnetic activity, and their pitch angle distribution are given. Comparison between the SPS data and energetic particle data indicates that the boundary between open and closed field lines on the dayside is associated with a sharp drop in the outer zone >1 kev electron fluxes. It is shown that these newly identified cusp fluxes provide the necessary energy to produce observed dayside auroral oval phenomena.

INTRODUCTION

Heikkila et al (1970), Winningham (1970) and Heikkila and Winningham (1971) gave the first definitive evidence for linking dayside "soft zone" fluxes with a magnetosheath source via the cusps in the dayside magnetosphere. The existence of magnetosheath plasma penetration to low altitudes had long been postulated by theoreticians and experimentalists alike (the reader is referred to the review in Winningham (1970) and Heikkila and Winningham (1971)). This paper will extend the dayside results presented in the earlier ISIS 1 papers.

Winningham (1970) identified the invariant latitude, denoted by Λ_{CL}, where outer zone fluxes cease and soft fluxes with magnetosheath characteristics begin as the last closed field line on the dayside. He further postulated this boundary to mark the beginning of interconnected terrestrial and interplanetary field lines. The invariant latitude, Λ_{CU}, where soft magnetosheath-like proton fluxes end was identified as marking the last merged field line which has free access to magnetosheath plasma. Electron fluxes are often observed above Λ_{CU} but they do not, in general, exhibit magnetosheath characteristics, and no protons are observed in the polar cap region. This terminology and its implied assumptions will be used in the remainder of this paper.

INSTRUMENTATION

ISIS 1 was launched into a 570 by 3500 km polar orbit (inclination 88.5°) on 30 January 1969. The ISIS 1 soft particle spectrometer (SPS) simultaneously measures the differential energy spectra of positive and negative particles in the energy range 10 ev to 12 kev per unit charge with a resolution of ± 40% (see Heikkila, et al., 1970 and Winningham, 1970 for a more detailed description). Results presented in this paper were obtained with a 15° x 35° collimator pointed perpendicular to the satellite spin axis.

The results obtained in the swept mode of operation are conveniently displayed as energy-time spectrograms. Each differential energy sweep of the instrument is shown as a separate line in the spectrogram (top portion of Figure 1a and b) with the density of the trace being modulated by the counting rate. A readout of 15 or less per sample is inhibited, with accumulation continuing during successive sampling intervals until >15 counts are accumulated. The middle and lower graphs of the spectrogram give the total number and energy flux over the 10 ev to 12 kev energy range.

OBSERVATIONS IN THE DAYSIDE HIGH-LATITUDE REGION

A pair of high resolution spectrograms (one spectrum every 1/2 sec or 4 km) are reproduced in Figure 1a and b. This pass, which began at 19:50:53 UT on 28 April 1969, occurred during the recovery phase ($K_p = 3^-$) of a storm that commenced at ~ 0300 hours UT on the same day. The magnetic local time was 1645 hours. At the beginning of this pass only low-energy electrons are observed in the polar cap region. The vertical bars appearing at 20 second intervals in the spectrogram are due to solar UV contamination. An isotropic flux of protons begins at 19:51:30 UT ($\Lambda_{CU} = 76.5°$) and continues to 19:53:26 UT ($\Lambda_{CL} = 73°$). Below Λ_{CL} the proton flux peaks at large pitch angles. Between Λ_{CL} and Λ_{CU} an isotropic flux of electrons with a spectral peak at ~ 100 ev is observed. Below Λ_{CL} the electron average energy increases, and the pitch angle distribution becomes anisotropic towards 90°.

It should be noted that electron fluxes for most cusp passes exhibit a greater variability than shown in Figure 1a (see Winningham (1970) for a larger collection of spectrograms). This pass was selected because of the large pitch angle scan and good angular resolution, not because it is "the typical pass."

Representative spectra from the cusp data in Figure 1a and b are given in Figure 2. The cusp electron spectrum at a pitch angle (α_p) of 29° is observed to have a peak at 100 ev as do a majority of the cusp spectra observed with ISIS 1 (Figure 3). Below ~ 60 ev a roughly power law component is observed in both cusp and outer zone spectra which is due to atmospheric photoelectrons (Heikkila, 1970) and secondaries. Outer zone electron spectra (Figure 2) gradually harden from an average energy of ~ 500 ev just below Λ_{CL} to ~ 1 kev when they go below threshold at $\Lambda = 68°$. Just below Λ_{CL} the electron flux is isotropic but rapidly becomes anisotropic towards 90° as the invariant latitude decreases. Proton spectra observed in the cusp region peak at ~ 600 ev (Figure 2) with a decrease in intensity towards higher and lower energies. Below Λ_{CL} the proton flux decreases in intensity, becomes harder, and is peaked at 90° pitch angle.

Rather than compare the spectra in Figure 2 with those in the magnetosheath for different periods as was done by Heikkila and Winningham (1970), comparison will be made in a later section between near concurrent IMP 5 (Frank, 1970) and ISIS 1 spectra recorded on 11 July 1969.

Close inspection of detailed spectral printouts reveals that up to 19:53:26 UT ($\Lambda = 73°$) electron spectra are identical to the cusp spectrum in Figure 2, and those after 19:53:36 (below $\Lambda = 72.9°$) are similar to the outer zone spectra in Figure 2. In the intervening region (10 seconds) the spectra appear to be an admixture of both. Burrows (private communication, 1971) indicates that above $\Lambda = 71.6°$ the trapped, energetic (>20 kev) electron fluxes begin a rapid drop to background. The >20 kev flux reaches 10% of maximum at 72.3° and background at 72.6°. The >200 kev detector (which has a larger geometric factor) reaches background at $\Lambda = 72.8°$. It thus appears that on this pass, hard outer zone electron fluxes extend up to the boundary between softer outer zone electrons and magnetosheath electrons. Winningham (1970) compared a larger number of passes and found similar results to the above. However, during very active periods fluxes of >20 kev electrons can be above background between Λ_{CL} and Λ_{CU}. Further intercomparison is being made and the results will be presented in a future paper.

PITCH ANGLE DISTRIBUTION

In the normal mode of SPS operation (one spectrum every two seconds) only three samples are obtained in one quadrant resulting in a coarse pitch angle distribution. In the all-radial sweep mode approximately 12 samples (one sweep every half second) are obtained in one quadrant. Figure 4 illustrates a typical high resolution electron and proton pitch angle distribution for the cusp fluxes shown in Figure 1a and b. As noted earlier soft electron and proton fluxes from the dayside cusp are observed from $\Lambda_{CL} = 73°$ to $\Lambda_{CU} = 76.5°$. During this period the pitch angle range scanned was 90° ± 71° at $\Lambda = 78°$ to 90° ± 80° at $\Lambda = 73°$. The large depressions in number and energy fluxes (see Figure 1a and b) occur when the instrument scans into the loss cone for upcoming particles (the large regular spikes are sun pulses).

Figure 4 shows that the number and energy flux for the primary electron beam (73 to 420 ev) in the cusp are isotropic up to $\alpha_p \sim 135°$ (α_p is the pitch angle for the normal to the detector aperture). Above 135° both the number and energy flux exhibit the same relative decrease in value. A particle at $\alpha_p = 135°$ and 140° (45° and 40° incident angles) will mirror at 700 and 200 km respectively (see Figure 4 for a graph of mirror heights appropriate to the altitude of the results presented in Figure 4). Particles incident at angles less than 38° (>142° return angle) will find their mirror points below 100 km. Thus particles observed above ~ 140° cannot be particles that have simply mirrored below the satellite.

Figure 5 gives electron spectra for pitch angles just prior to and after the decrease in Figure 4. The spectra at $\alpha_p = 144°$ and 151° are observed to be similar in shape to the one at 135° but decreased in amplitude. This seems to indicate that a significant amount of elastic scattering exists in the ionosphere below the cusp. As the pitch angle increases, the peak in the >73 ev range is lost and the spectra appear to be due to backscatter of secondaries and degraded primaries. The return flux for particles inside the loss cone is observed to be much smaller for soft outer zone fluxes (see Figure 1a at 19:53:38 UT). As mentioned earlier the average energy for the soft outer zone spectra is 5 to 10 times that of the cusp spectra. The 500 ev outer zone electrons thus deposit a greater fraction of their incident energy in the ionosphere as compared to the 100 ev cusp electrons. This difference in the fraction of the incident energy flux lost (i.e. different albedos) can probably be explained by the manner in which energy is lost as a function of incident particle energy. The ~ 100 ev cusp electrons begin their energy loss at very high altitudes (~600 km) whereas the ~ 500 ev outer zone electrons begin theirs at ~ 400 km (Rees, 1964). If at higher altitudes processes such as coulomb scattering off heavy ions, collisional excitation, or weak wave-particle interaction dominate over ionization then large angular scattering is possible without large energy losses. This would result in a large albedo electron flux with a spectrum similar to the incident spectrum (see Figure 5). As the altitude of the energy loss region decreases (i.e. increasing particle energy) ionization, with its accompanying large incremental energy loss, will probably become the major loss mechanism. If present, the albedo flux would be composed mainly of highly degraded primaries and secondaries bearing little resemblance to the incident spectrum. This is consistent with the differences observed in cusp and outer zone albedo fluxes in Figure 1a.

An alternative explanation to the above would be an electrostatic double layer in the cusp below the satellite. The parallel electric field of the double layer would raise the mirror heights and thus decrease the energy loss. Assuming a 100V potential to exist between the satellite (2600 km) and the 100 ev maximum loss region (~300 km), a field of ~ 50 μv/m would result. This value is not prohibitively large but has one drawback. Such a field would accelerate ionospheric electrons into the energy range of ISIS 1. No such fluxes are observed on 28 April 1969 or other ISIS 1 passes which scan from 0 to 180° pitch angle.

Figure 4 indicates that the loss process for protons occurs in the altitude range below ~ 700 km (α_p = 135). The albedo proton flux above 135° is observed to be vanishingly small. This is consistent with the usual assumption of loss from the primary proton beam by charge exchange (i.e. conversion to hydrogen which is not measured by the SPS even if it is back-scattered).

Assuming that both electron and proton angular distributions are isotropic over the upper hemisphere ($10° \leq \alpha_p \leq 170°$ in the cusp region), the fraction of the incident energy that is lost can be calculated. For protons in Figure 1b it is obvious (Figure 4) that all the incident primary energy (1.0×10^{-1} ergs/cm^2 sec) is deposited in the ionosphere. Using an average energy of ~ 1 kev and the results of Eather (1967) this energy loss corresponds to ~ 5 R of Hβ which is in good agreement with recent airborne measurements of the dayside aurora (Eather & Mende, 1971a). According to Figure 4 approximately 60% the incident primary electron energy flux of 2.5×10^{-1} ergs/cm^2 sec is deposited in the ionosphere. Again these results are seen to be in quantitative agreement with Eather and Mende's (1971a) inference that particles causing distinct dayside aurora deposit ~ 1.3×10^{-1} ergs/cm^2 sec^{-1} into the ionosphere and have an average energy of ~ 100 to 200 ev (see Figure 3).

EXTENT OF MAGNETOSHEATH PLASMA PENETRATION AND ITS DEPENDENCE ON K_p

As pointed out earlier Λ_{CL} is defined empirically as the boundary between hard, structureless outer zone fluxes and softer, structured cusp fluxes. Physically Λ_{CL} is the last closed magnetic field line on which significant bounce motion between hemispheres can be maintained (i.e. closed on the dayside of the magnetosphere). Between Λ_{CL} and Λ_{CU} (the upper limit of cusp proton fluxes) the ISIS 1 data indicates that terrestrial field lines have continuous free access to magnetosheath plasma. Figure 6 illustrates the extent of this region of magnetosheath plasma penetration in magnetic local time (8 to 16 hours). Data for a given hour interval is averaged and plotted at the mid-point of the interval. The largest sampling density is in the forenoon, $K_p \leq 3$ region with less statistical accuracy for other points. The lower limit of penetration, Λ_{CL}, is observed to be largest at local magnetic noon with a decrease before and after midday. Also Λ_{CL} is observed to move progressively equatorward with increasing K_p. The upper limit, Λ_{CU}, of cusp fluxes is observed to be less responsive to changes in K_p (it should be noted, however, that due to orbit parameters the sampling density for Λ_{CU} is much less than Λ_{CL}). Also Λ_{CU} does not exhibit the same statistical magnetic time dependence as Λ_{CL}. For some passes at increased K_p, Λ_{CU} is observed to track Λ_{CL} (i.e. the whole cusp moves equatorward without an appreciable change in width). A comparison with changes in solar wind and interplanetary magnetic conditions would probably be more appropriate than the above comparison to K_p. Such a comparison is presently being undertaken and will be reported in a future paper.

The above results do not imply that softer fluxes of electrons and protons do not exist before and after 8 and 16 hours magnetic local time. Significant fluxes of low energy particles are indeed present outside these limits but their spectra peak at higher energies and do not in general exhibit magnetosheath characteristics.

For magnetically quiet periods the boundary (in MLT) of magnetosheath fluxes can be quite sharp. During days when the local time is ~ 7 to 8 (or 16 to 17) hours, the dipole wobble causes a large diurnal variation in magnetic local time. When the dipole tilt results in times inside the 8 to 16 hour magnetic time interval, magnetosheath fluxes are observed; and when MLT is outside this period, non-magnetosheath fluxes are observed. During more disturbed periods magnetosheath fluxes are observed as early as 0500 MLT and as late as 1800 MLT as evidenced by Figure 1.

Using the results of Fairfield (1968) the 8 to 16 hour magnetic time interval at ISIS 1 altitudes maps into the magnetic equatorial plane at ~ 06 and 18 hours local time (i.e. solar dawn-dusk). Thus if we take these results at face value, magnetosheath plasma has access to the magnetosphere across its entire front side during quiet periods and over a larger extent during disturbed periods. It will be extremely interesting in terms of magnetospheric structure and dynamics if the above results inferred from low-altitude measurements are verified by a comprehensive in situ survey.

COMPARISON WITH OTHER OBSERVATIONS OF DAYSIDE CUSP FLXUES

Winningham (1970) and Heikkila and Winningham (1971) compared their dayside high-latitude spectra with earlier magnetosheath spectra and inferred that the magnetosheath is the source for the dayside "soft zone". This comparison obviously suffers in that the measurements compared are neither concurrent in time and meridian nor obtained for similar solar wind and geomagnetic conditions. Also Winningham's (1970) and Heikkila and Winningham's (1971) observations were obtained during the recovery phase of a magnetic storm where K_p was 5+ and ΣK_p equalled 41+. These results (mainly the latitudinal width of the cusp) could thus be construed as a transient phenomena occuring only during large storms. As pointed out earlier in this work and that of Winningham (1970) this is not the case, however.

Figure 7 details a comparison of near coincident electron spectra obtained with the high-latitude, high-inclination IMP 5 spacecraft (Frank, 1970) and the low-altitude ISIS 1 polar satellite on 11 July 1969. These observations were made within ~ 2 hours of universal and local time and during a relatively quiet period with $K_p = 1$, $A_p = 6$, and $\Sigma K_p = 11$. The electron average energy is ~ 60 eV and the electron number and energy fluxes are lower than normal (presumably a result of the quieter solar wind conditions, V_H+ = 332 km/sec and $N_H+ = 3.7\ cm^{-3}$). For the region of energy overlap the ISIS 1 cusp spectrum is observed to be in quantitative agreement with the magnetosheath and mid-altitude cusp spectra obtained concurrently by IMP 5. The outer zone electron spectra are also observed to be in quantitative agreement (the outer zone fluxes were also much lower here than during more disturbed periods). The width of the cusp was however at least 2.5° even for these low K_p and solar wind conditions. Λ_{CU} and the actual width could not be determined because data transmission began within the cusp region. The above results are in agreement with other quiet-time ISIS 1 cusp data and indicate the large width to be a permanent feature.

The proton directional number flux ($3 \times 10^6/cm^2$ ster sec) was also low for this cusp traversal and the proton average energy was low (~300 ev). This is also quite likely a result of the quiet solar wind (and presumably magnetosheath) conditions during this period.

As discussed earlier fluxes of protons and electrons with magnetosheath characteristics are observed nearly continuously in a 2° to 3° zone (Figure 6) above the limit of closed field lines (evidenced by a large drop in the outer zone fluxes). Frank and Ackerson (1971) give two examples of very narrow (20-30 km or $\Delta\Lambda = 0.2°$) electron spikes obtained with INJUN 5 which they identify as the low-altitude signature of the cusp. At $\Lambda_{CU} = 76.5°$ (19:51:30 UT) in Figure 1a a large increase in both the number and energy flux is observed, but the average energy and spectral shape are similar to the remainder of the cusp. This feature is three seconds (~ 21 km) wide and is probably similar to the narrow (20-30 km) features observed by Frank and Ackerson (1971) (see discussion section). Other examples of this narrow feature have been observed in the ISIS 1 data (see Winningham, 1970) and are generally found close to either Λ_{CL} or Λ_{CU}.

An apparent discrepancy also exists between the ISIS 1 and IMP 5 results. Frank (1970) observed 690 to 1100 eV protons to lie poleward of 305 to 510 ev electrons in the mid-altitude cusp. In general no such separation is observed in the ISIS data and in particular no such separation is found in the data at 0900 UT on 11 July 1969.

Russell et al. (1970) reported a high-altitude observation of the northern dayside cusp at 45° geomagnetic latitude during the large storm of

October 31-November 1, 1968. During quiet periods the inclination of OGO 5 does not allow it to traverse the cusp. They concluded the cusp to be moving back and forth at velocities comparable to the satellite in response to changes in geomagnetic and solar wind parameters. During the storm of February 2-3, 1969 Λ_{CL} was observed to move to as low as 67° at 1000 hours local time with ISIS 1. The cusp widths for two passes at $K_p = 6^-$ and 7 and low Λ_{CL} during this period were no larger than usual indicating the varying response of the cusp to changes in K_p. During a small storm on 8 June 1969 the northern cusp was observed to be 8° (~2000 km) wide at 3500 km (Λ_{CL} = 75.5°, MLT = 0100 hours) for a time when K_p was 3^- (3^- was also the maximum K_p). This would correspond to ~800 km at auroral heights. As mentioned earlier in this paper and in Russell (1971) changes in the cusp are probably more intimately related to changes in the solar wind and interplanetary magnetic field than to changes in geophysical parameters.

DISCUSSION

The results presented in this paper and those of Frank (1970), Frank and Ackerson (1971), Heikkila and Winningham (1971), Russell et al. (1971), and Winningham (1970) have established the existence of two cusp-like regions in the dayside magnetosphere and the penetration of magnetosheath plasma to low altitudes through them. The main difficulty in reconciling these various measurements lies in the width and structure of the cusp at auroral heights. Frank (1970), using IMP 5 data indicates the low-altitude width should map to 20 to 30 km ($\Delta\Lambda$ = 0.2°) at the ionosphere, and reports a feature of the INJUN-5 data (Frank and Ackerson, 1970) which would support this. On the other hand the ISIS 1 data indicates a region which is on the average ~ 2 to 3° wide at low altitudes.

The discrepancy between the ISIS 1 data and the projection of the IMP 5 data onto the ionosphere can be resolved, I believe, in the following way. Frank (1970) indicates the latitudinal width of the cusp to be ~ 1 R_E at its high altitude limit (which lies at ~ 10 R_E). If the results presented in this paper are correct, then the cusp will extend over the complete front surface of the magnetosphere. The length of the cusp will thus be ~ $\Pi \times 10\ R_E$ = 2×10^5 km which results in a magnetopause cusp area of $dA_s = 1.3 \times 10^9\ km^2$. Using a value of B at 10 R_E of $B_s = 50\ \gamma$ (Fairfield, private communication, 1971) and B_I = .5 gauss at auroral heights the ratio of $\frac{B_s}{B_I}$ will be 10^{-3}. Using the conversation of flux, dA_I (the cusp area at low altitudes) is given by

$$dA_I = \frac{B_s}{B_I}\ dA_s$$

$$dA_I = 1.3 \times 10^6\ km^2$$

The longitudinal extent of magnetosheath fluxes reported in this paper is ~ 4000 km which results in a latitudinal width of ~ 320 km (3°) at auroral heights which is in good agreement with the ISIS 1 observations. Frank (1970) also indicates that the cusp width does not increase more than a factor of 2 even for disturbed conditions. Everything else being the same, a factor of 2 increase in width at the magnetopause would result in a width of ~1900 km at 3500 km. This is also in good agreement with the maximum cusp width of 2000 km observed with ISIS 1 at this altitude on 8 June 1969, as mentioned earlier.

The difference in widths observed at low-altitudes by INJUN 5 and ISIS 1 could be the result of different instrumental sensitivities. Another, and more likely, possibility exists in the impression gained from a spectrogram presentation and the inferences made therefrom. Frank and Ackerson (1971) associated the sharp, low-energy burst at 23:31:00 UT (their plate 6a) with the low-altitude cusp. However if the low-latitude, low-altitude boundary of the cusp is associated with the sharp change (from 2000 to 150 ev) in average energy at 23:30:05 UT (see Figure 16, Frank and Ackerson, 1971) and the upper boundary with the sharp burst at 23:31:00 UT, then the width of the cusp would be ~ 2°. This would result in good agreement between measurements made with ISIS 1 and INJUN 5.

Frank (1971), in a recent letter, has indicated that his original estimate (Frank, 1970) of the low-altitude cusp width was much smaller than the average value of 200 km obtained from a larger set of IMP 5 data. This updated width brings the IMP 5 observations into much closer agreement with those observed by ISIS 1 and calculated in this section. However, this larger set of IMP 5 data still indicated two distinct, yet not mutually exclusive, field aligned 'sheets' of proton and electron fluxes (with electrons lying equatorward of protons) at mid altitudes in the cusp. No evidence of such clear separation can be found in the ISIS 1 data. Protons, if above the instrument threshold, are always coincident with electron fluxes. Electron fluxes in the cusp do have bursts superimposed on a background continuum flux but these electron bursts have no counterpart in the accompanying proton fluxes. Also no evidence for proton precipitation poleward of electron precipitation is observed in airborne photometric data (Eather and Mende, 1971b). If this sheet structure is a permanent feature of the cusp at mid-altitudes it then appears that "remixing" of the plasma must occur between ~ 5 R_E and 1.5 R_E. The resolution of this question should be possibly by a careful intercomparison of the available ground based and satellite data pertinent to the dayside magnetospheric cusps.

CONCLUSIONS

From the data presented in this and earlier works by Winningham (1970), and Heikkila and Winningham (1971) the following conclusions are reached:

1. The long postulated free access of magnetosheath plasma to ionospheric heights does exist,

2. Access of magnetosheath plasma extends from 0800 to 1600 MLT (magnetic local time) and is on the average 2° to 3° of invariant latitude wide at auroral heights,

3. Using the results of Fairfield (1968) penetration through the dayside magnetospheric cusps occurs over the complete front side of the magnetosphere and during disturbed periods possibly over a larger extent,

4. The postulated separation of proton and electron fluxes at mid-altitudes in the dayside cusps is not present at heights $\leq 1.5\ R_E$,

5. The dominant effect of increased magnetic activity is an equatorward motion of the boundary between open and closed field lines with the largest cusp width being ~ a factor of 2 greater than the average,

6. The energy and number flux and particle average energies are sufficient to explain observed dayside auroral phenomena, and

7. Electron spectra observed concurrently at low and mid-altitudes in the cusp and outer zone are similar in shape and magnitude.

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FIGURE CAPTIONS

Figure 1a. Electron spectrogram for 28 April 1969 at 19:50:53 UT.

Figure 1b. Proton spectrogram for 28 April 1969 at 19:50:53 UT.

Figure 2. Electron and proton differential spectra for the data contained in Figure 1a and b. Cusp spectra were obtained for the period 19:51:57 to 19:52:07 UT. The outer zone spectrum is for 19:54:01 UT.

Figure 3. Frequency of occurrence for the peak energy of the primary electron spectrum in the dayside magnetospheric cusp.

Figure 4. Normalized proton and electron pitch angle distributions for the energy range 73 to 420 ev. These distributions are for the period 19:51:57 to 19:52:07 UT in Figure 1. Unity represents 2.5×10^{8} cm^{-2} $ster^{-1}$ sec^{-1} and 6.0×10^{-2} ergs cm^{-2} $ster^{-1}$ sec^{-1} for electrons; and 1.0×10^{7} cm^{-2} $ster^{-1}$ sec^{-1} and 3.0×10^{-2} ergs cm^{-2} $ster^{-1}$ sec^{-1} for protons.

Figure 5. Electron spectra for the data contained in Figure 4.

Figure 6. Extent of magnetosheath plasma penetration in magnetic local time and invariant latitude as a function of K_p.

Figure 7. Comparison of outer zone and cusp spectra obtained within 2 hours of local and universal time on 11 July 1969 with ISIS 1 and IMP 5.

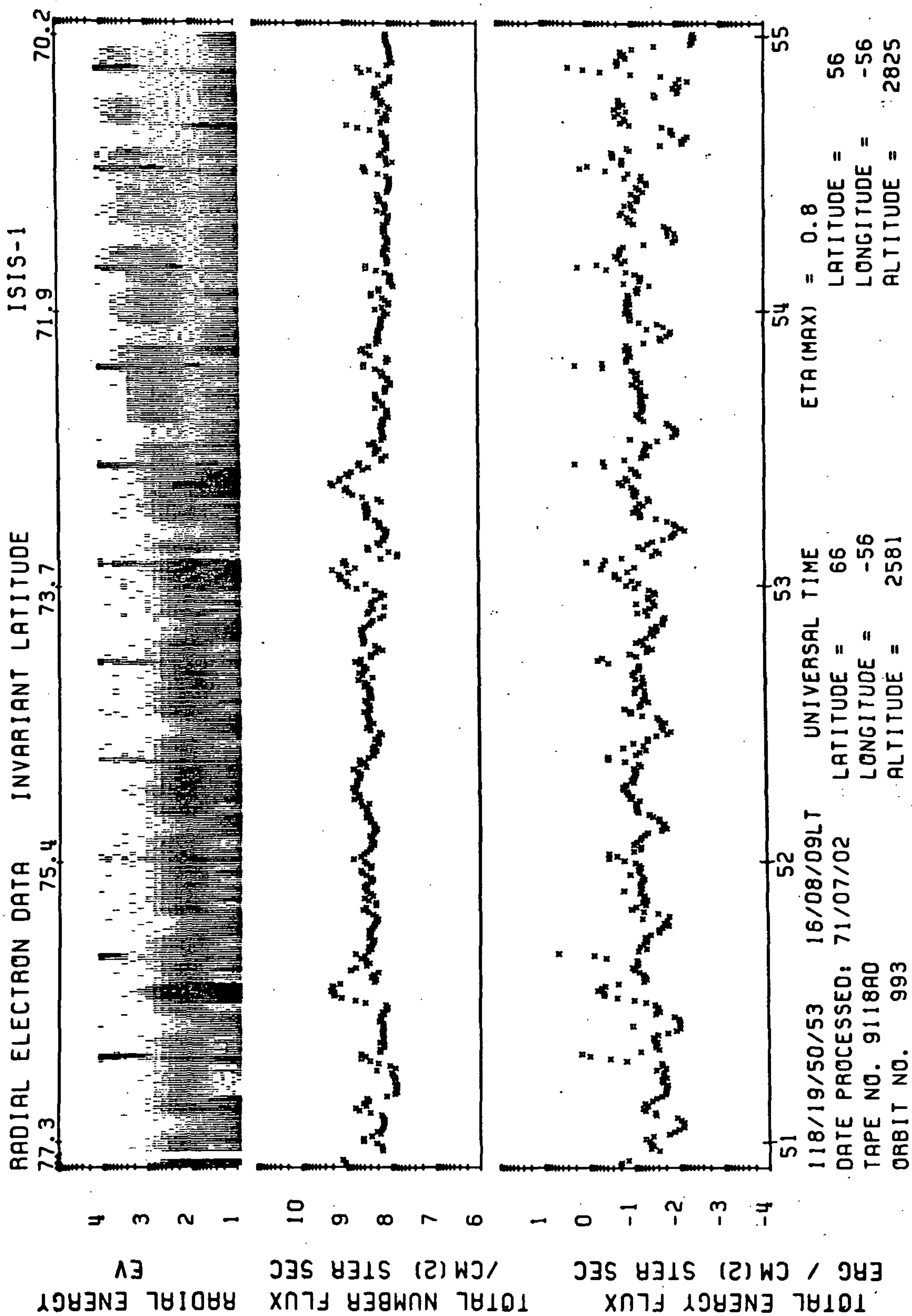
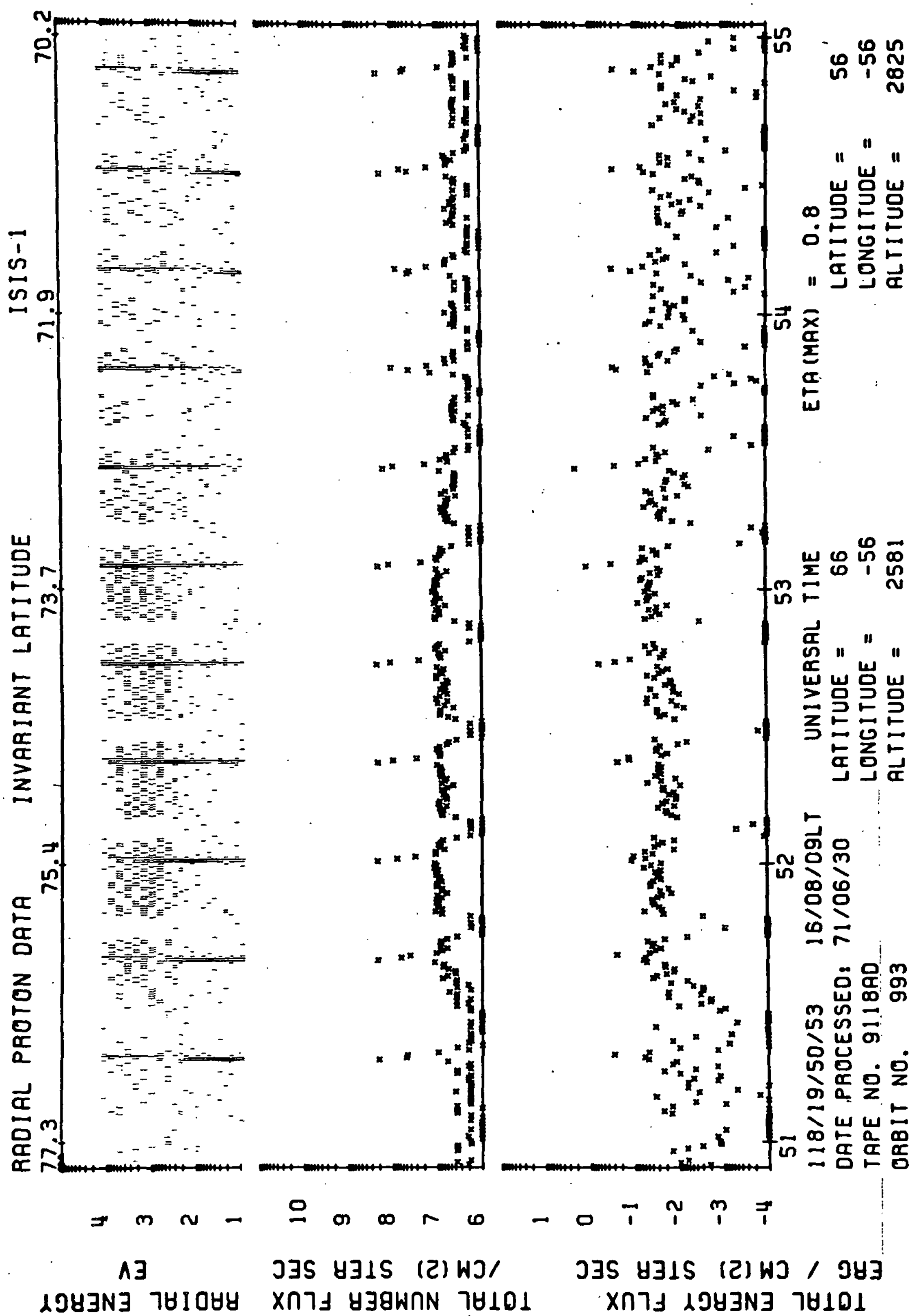

RADIAL ELECTRON DATA
INVARIANT LATITUDE
ISIS-1
77.3
75.4
73.7
71.9
70.2
RADIAL ENERGY
EV
TOTAL NUMBER FLUX
/CM(2) STER SEC
TOTAL ENERGY FLUX
ERG / CM(2) STER SEC
51
52
53
54
55
118/19/50/53
16/08/09LT
UNIVERSAL TIME
DATE PROCESSED: 71/07/02
TAPE NO. 9118AD
ORBIT NO. 993
LATITUDE = 66
LONGITUDE = -56
ALTITUDE = 2581
ETA(MAX) = 0.8
LATITUDE = 56
LONGITUDE = -56
ALTITUDE = 2825

Figure 1a.



RADIAL PROTON DATA
INVARIANT LATITUDE
ISIS-1
77.3
75.4
73.7
71.9
70.2
51
52
53
54
55
118/19/50/53
16/08/09LT
UNIVERSAL TIME
ETA(MAX) = 0.8
DATE PROCESSED: 71/06/30
TAPE NO. 9118AD
ORBIT NO. 993
LATITUDE = 66
LONGITUDE = -56
ALTITUDE = 2581
LATITUDE = 56
LONGITUDE = -56
ALTITUDE = 2825
RADIAL ENERGY
EV
TOTAL NUMBER FLUX
/CM(2) STER SEC
TOTAL ENERGY FLUX
ERG / CM(2) STER SEC

Figure 1b.

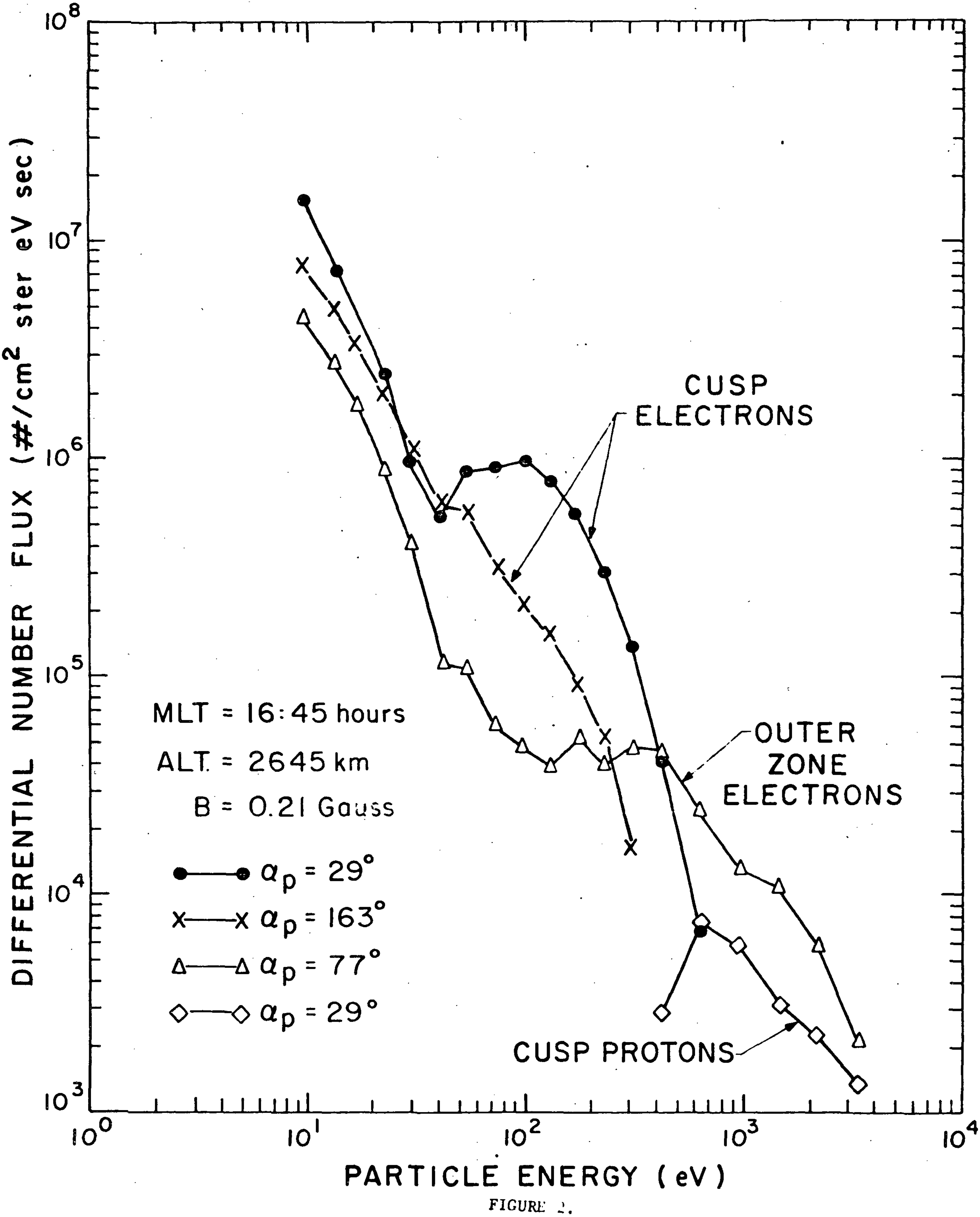

DIFFERENTIAL NUMBER FLUX (#/cm² ster eV sec)
PARTICLE ENERGY (eV)
CUSP ELECTRONS
OUTER ZONE ELECTRONS
CUSP PROTONS
MLT = 16:45 hours
ALT. = 2645 km
B = 0.21 Gauss
αp = 29°
αp = 163°
αp = 77°
αp = 29°

FIGURE 2.

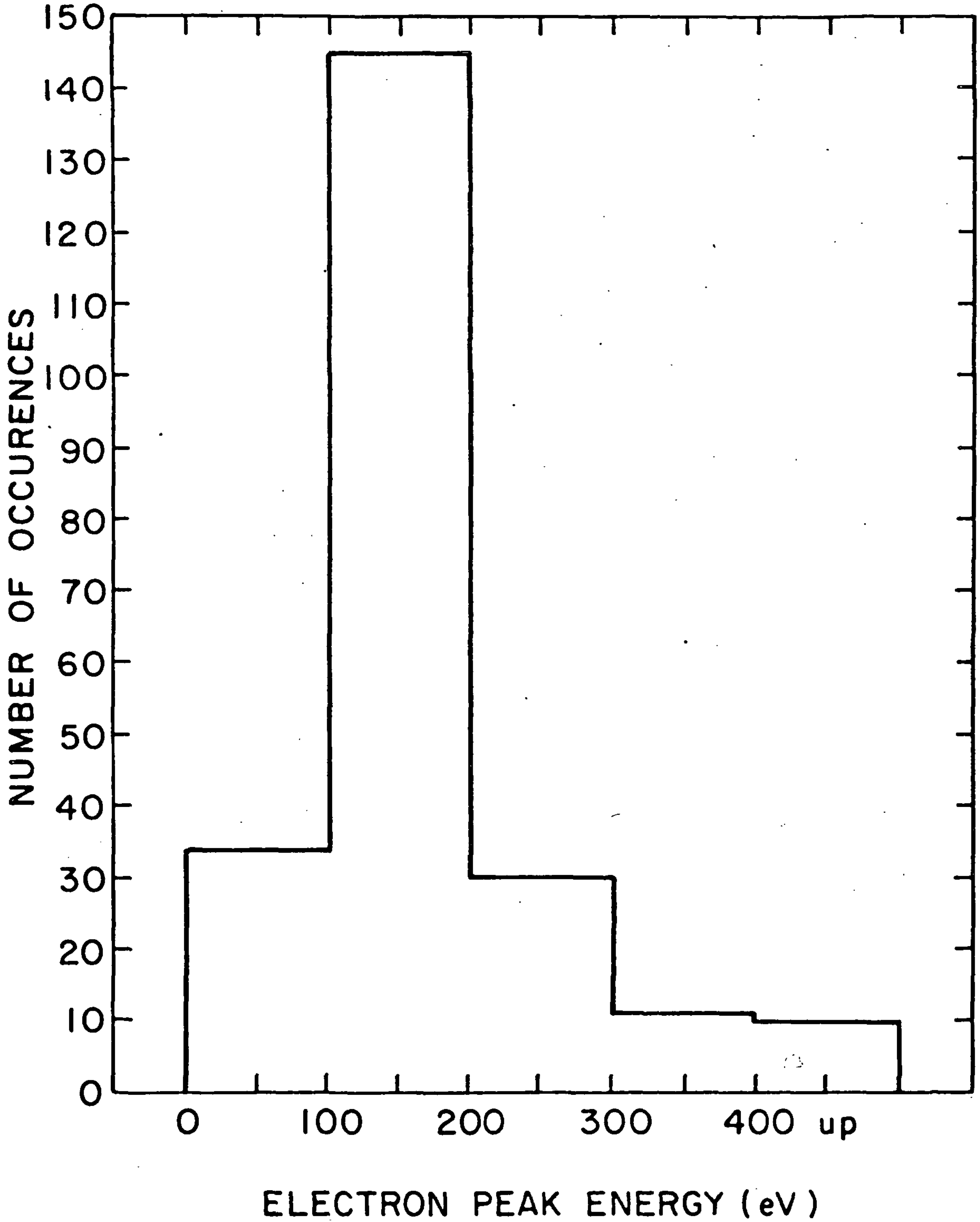

150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
NUMBER OF OCCURENCES
0
100
200
300
400 up
ELECTRON PEAK ENERGY (eV)

FIGURE 3.

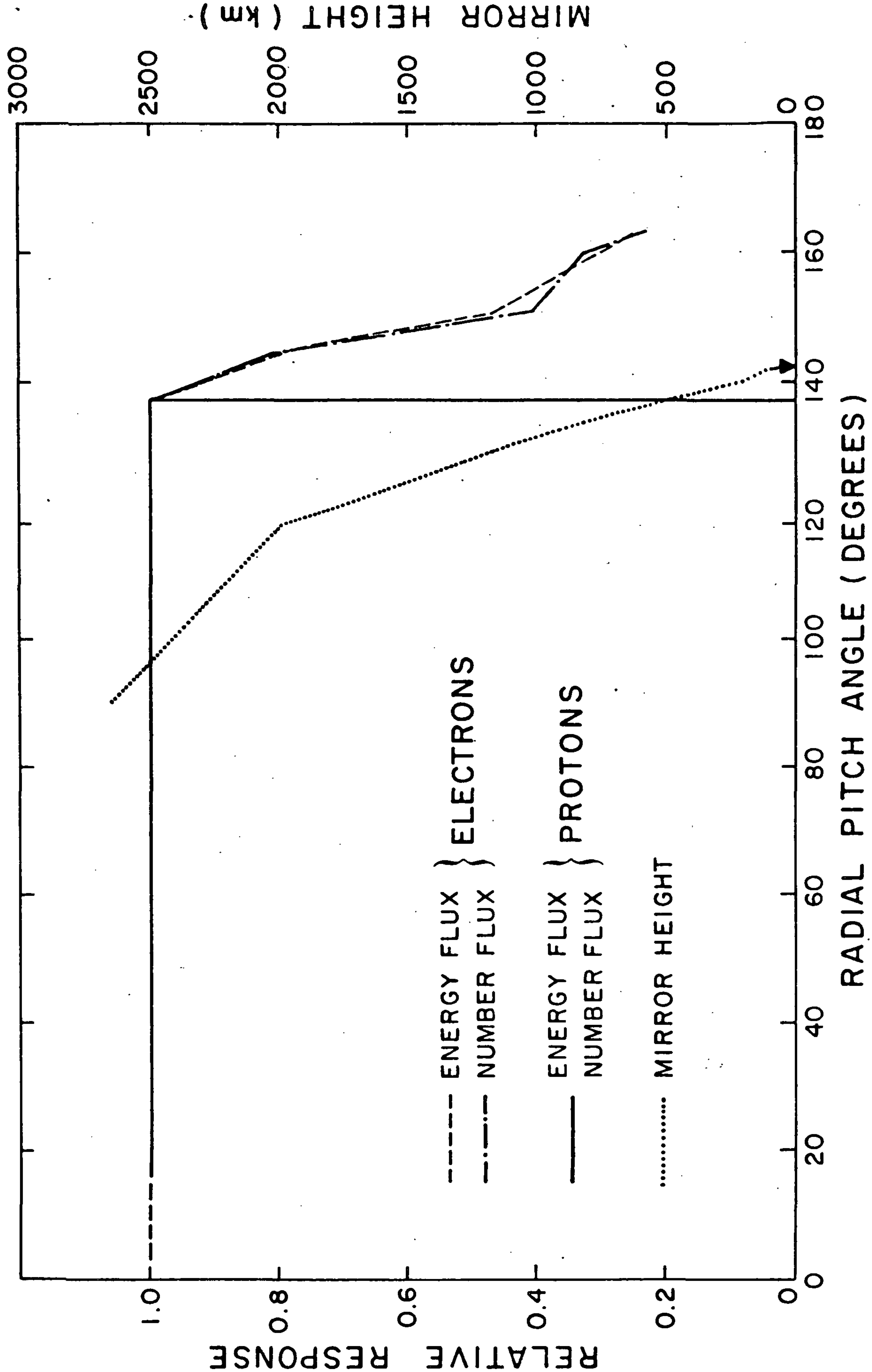
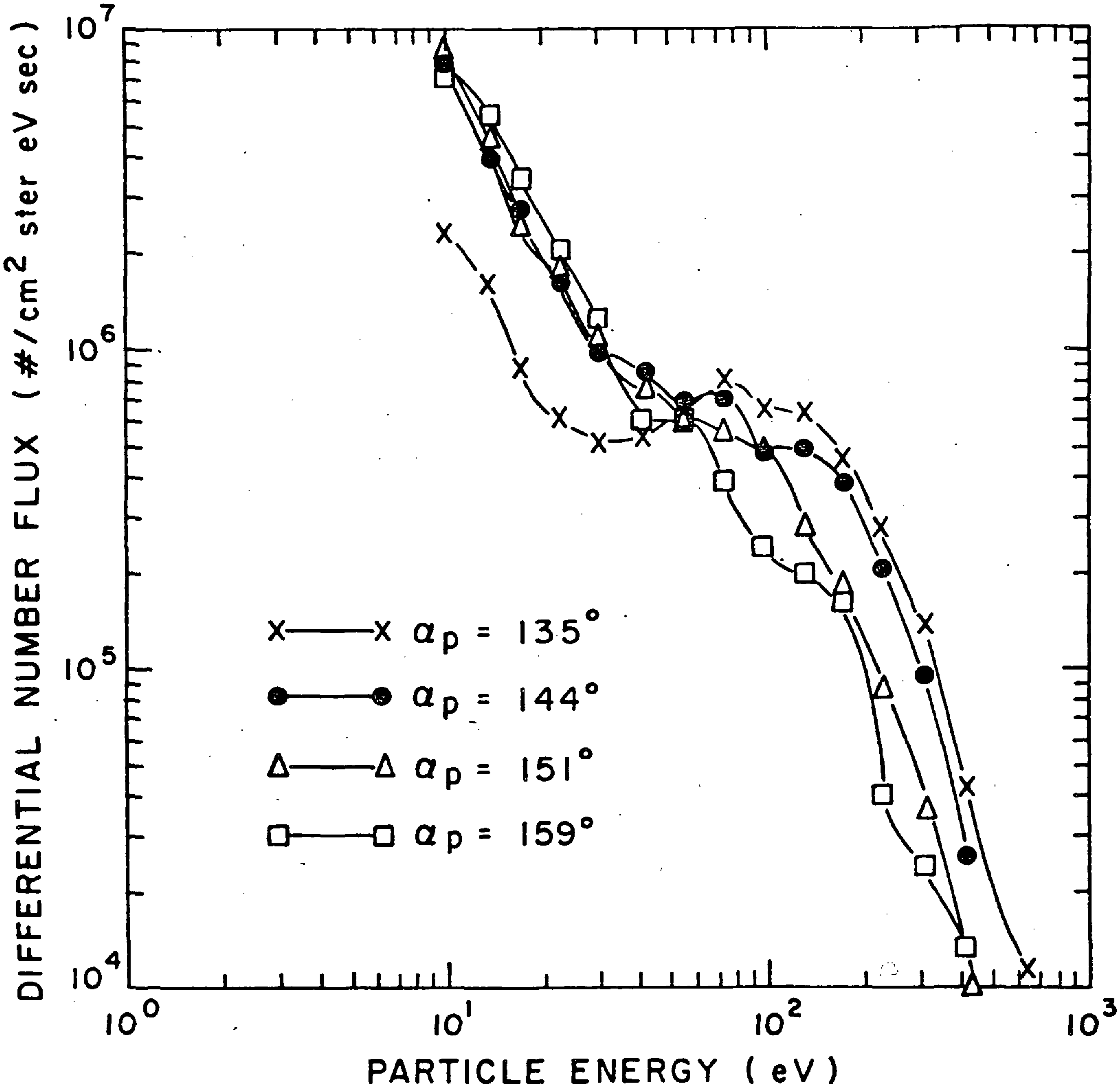
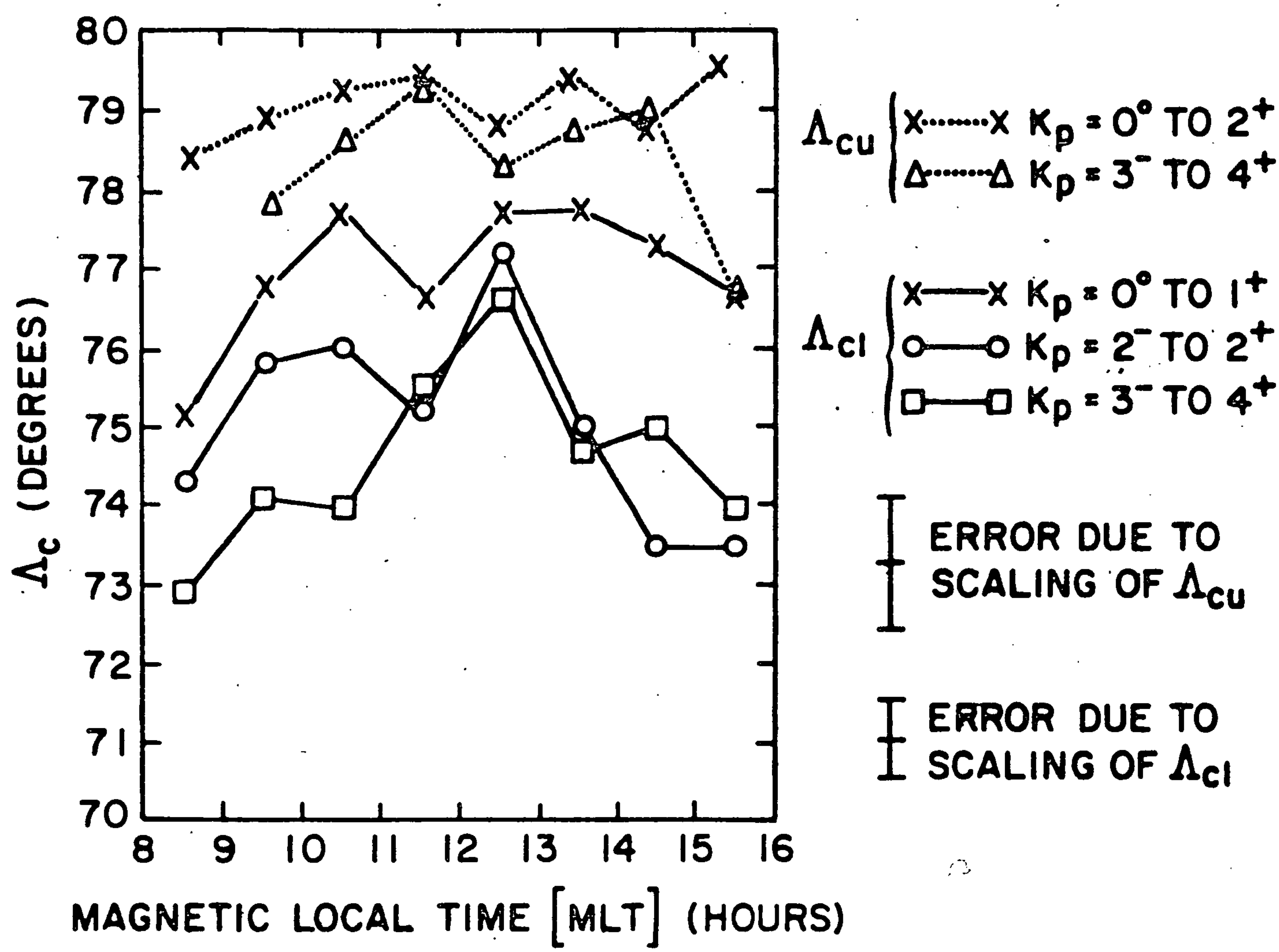

MIRROR HEIGHT (km)
3000
2500
2000
1500
1000
500
0
RELATIVE RESPONSE
1.0
0.8
0.6
0.4
0.2
0
RADIAL PITCH ANGLE (DEGREES)
0
20
40
60
80
100
120
140
160
180
ENERGY FLUX
NUMBER FLUX
ELECTRONS
ENERGY FLUX
NUMBER FLUX
PROTONS
MIRROR HEIGHT

FIGURE 4.



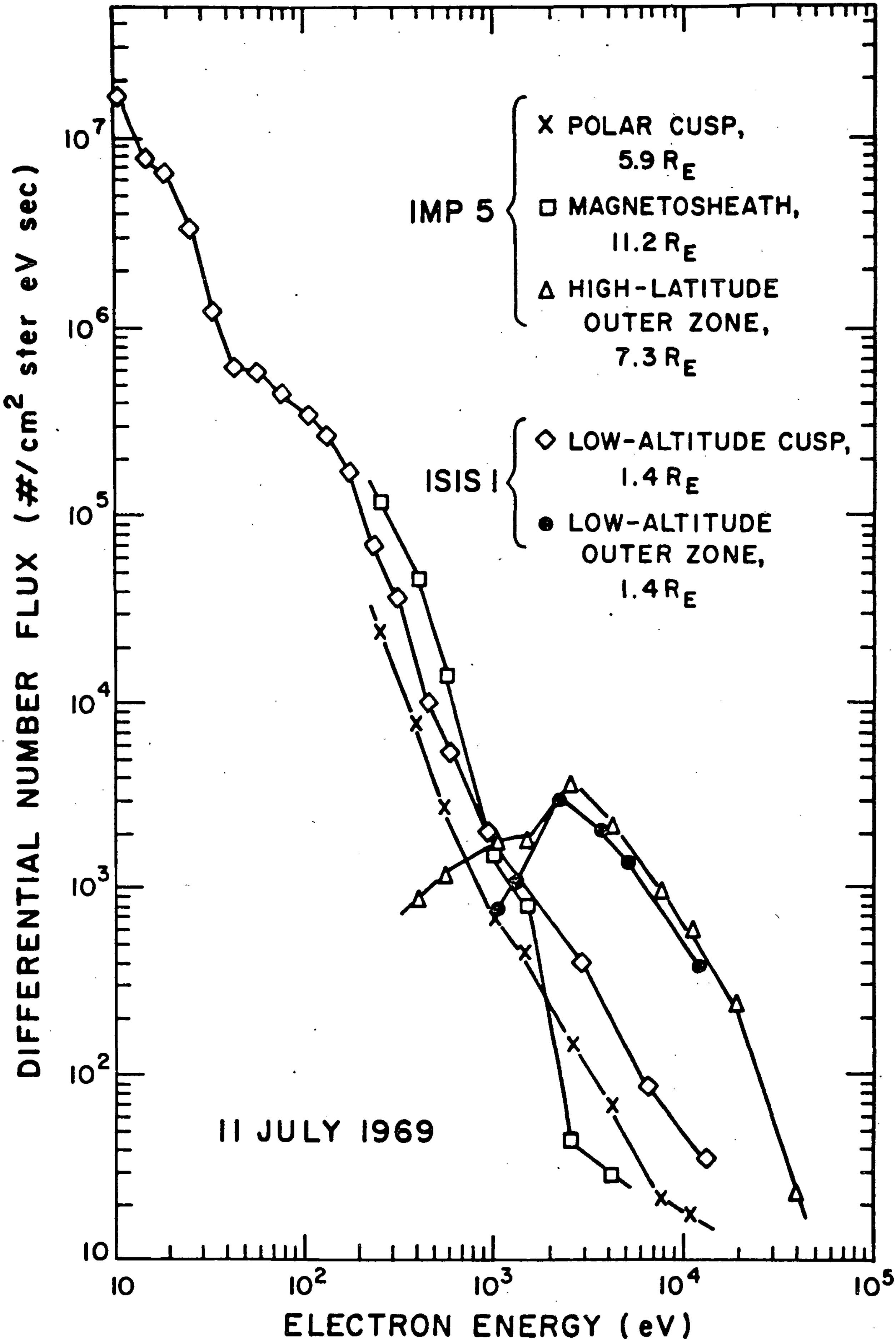
DIFFERENTIAL NUMBER FLUX (#/cm^2 ster eV sec)
10^7
10^6
10^5
10^4
10^0
10^1
10^2
10^3
PARTICLE ENERGY (eV)
α_p = 135°
α_p = 144°
α_p = 151°
α_p = 159°

FIGURE 5.



80
79
78
77
76
75
74
73
72
71
70
Λ_c (DEGREES)
8
9
10
11
12
13
14
15
16
MAGNETIC LOCAL TIME [MLT] (HOURS)
Λ_{cu}
K_p = 0° TO 2+
K_p = 3- TO 4+
Λ_{cl}
K_p = 0° TO 1+
K_p = 2- TO 2+
K_p = 3- TO 4+
ERROR DUE TO SCALING OF Λ_{cu}
ERROR DUE TO SCALING OF Λ_{cl}

FIGURE 6.


X POLAR CUSP, 5.9 R_E
□ MAGNETOSHEATH, 11.2 R_E
Δ HIGH-LATITUDE OUTER ZONE, 7.3 R_E
IMP 5
◇ LOW-ALTITUDE CUSP, 1.4 R_E
● LOW-ALTITUDE OUTER ZONE, 1.4 R_E
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DIFFERENTIAL NUMBER FLUX (#/cm^2 ster eV sec)
ELECTRON ENERGY (eV)
10
10^2
10^3
10^4
10^5
10^6
10^7

FIGURE 7.